

Shallow and diffuse spin-orbit potential for proton elastic scattering from neutron-rich helium isotopes at 71 MeV/nucleon

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Vector analyzing powers for proton elastic scattering from ^8He at 71 MeV/nucleon have been measured using a solid polarized proton target operated in a low magnetic field of 0.1 T. The spin-orbit potential obtained from a phenomenological optical model analysis is found to be significantly shallower and more diffuse than the global systematics of stable nuclei, which is an indication that the spin-orbit potential is modified for scattering involving neutron-rich nuclei. A close similarity between the matter radius and the root-mean-square radius of the spin-orbit potential is also identified.

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The strong spin-orbit coupling in atomic nuclei plays an important role in nuclear structure and reactions. One good example is the spin-orbit splitting of single-particle levels, which is a key ingredient for the success of the nuclear shell model [1, 2]. Spin-orbit coupling is also responsible for many other phenomena such as the dominance of the prolate shape and the emergence of the isomeric intruder state. Moreover, in terms of nuclear reactions, spin-orbit coupling is responsible for the polarization effects in elastic scattering. There has recently been renewed interest in spin-orbit coupling since it is predicted to be modified in neutron-rich nuclei. A number of experimental results suggest a change in the shell structure of neutron-rich nuclei that could be explained by a reduction in the spin-orbit splitting [3–5]. However, there has been no experimental study examining how the spin-orbit coupling is modified in nuclear reactions of unstable nuclei.

Spin asymmetry in proton–nucleus (p - A) elastic scattering is a prominent manifestation of the spin-orbit coupling in nuclear reactions. The coupling is generally represented by a spin-orbit term in the optical model potential, i.e., the spin-orbit potential. Current understanding of this potential has been based on extensive measurements and analysis of the vector analyzing powers for elastic scattering of polarized protons from various stable nuclei over a wide energy range [6–11]. It is now well established that the shape and magnitude of the spin-

orbit potential does not depend strongly on the target nucleus. The shape is reasonably expressed by a derivative of the density distribution [12–14], while the magnitude is almost independent of the mass number [10, 11]. However, whether these systematics hold even in regions far from the stability line is still an open question. The structure of neutron-rich nuclei often shows distinctive features such as a very diffuse nuclear surface, a neutron-skin and halo, and a difference between the radial dependence of the proton and neutron distributions. From the surface nature of the spin-orbit coupling, we can expect that the spin-orbit potential is modified in the neutron-rich region. In this letter we determine the spin-orbit potential between a proton and a typical neutron-rich nucleus ^8He and investigate the effect of the exotic structure of the neutron-rich nucleus on the spin-orbit coupling in p - A scattering.

Determination of the spin-orbit potential requires vector analyzing power data, and until several years ago, such data could not be obtained in the experiment with a radioactive-ion beam. This was due to the lack of polarized targets that can be operated at a low magnetic field of $\ll 1$ T. However, we were able to construct a solid polarized proton target at 0.1 T based on a new polarizing method [15–18] and have applied it to scattering experiments of ^6He at 71 MeV/nucleon [17, 19, 20].

Recently, we have measured the vector analyzing powers for proton elastic scattering from ^8He at 71 MeV/nucleon. These neutron-rich helium isotopes are suitable for exploring the modification of spin-orbit potential, since they have large neutron-excess ratios $(N - Z)/A$ and significantly diffuse density distributions. The data are analyzed with a phenomenological optical model to discuss the overall characteristics of the spin-

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orbit interaction with a least-biased approach. Details of both the measurements and analysis are reported in this paper.

The analyzing power measurement of p - ^8He elastic scattering was carried out at RI Beam Factory operated by RIKEN Nishina Center and Center for Nuclear Study, University of Tokyo. The ^8He beam was produced by a projectile fragmentation reaction of an ^{18}O beam with an energy of 100 MeV/nucleon bombarding a 13-mm thick Be target. The ^8He particles were then separated by the RIKEN Projectile-fragment Separator (RIPS) [21]. The energy of the ^8He beam was 71.0 ± 1.4 MeV/nucleon at the center of the secondary target. The typical intensity and purity of the beam were 1.5×10^5 pps and 77 %, respectively. As a secondary target, the solid polarized proton target [15–18] was placed at the final focal plane of the RIPS. The target was operated under a low magnetic field of 91 mT, which allowed us to detect low-energy (~ 10 MeV) recoil protons under inverse kinematics conditions. The average target polarization was 11.3 ± 2.6 %.

The detector system is same as that used in the p - ^6He measurement described in Ref. [20] except for the recoil proton detectors. To achieve higher angular and energy resolutions for the recoil protons, we used multi-wire drift chambers (MWDCs) and CsI(Tl) scintillators with a Si PIN photodiode readout. The position resolution of the MWDCs was $200 \mu\text{m}$ (full width half maximum). This corresponds to an angular resolution of 0.05° in sigma in the center-of-mass system, which is one order of magnitude better than that in the p - ^6He measurement. The effects of the magnetic field on the proton scattering angle, which was comparable to or smaller than the detector resolution, were properly corrected in the data analysis. Using the correlation between the recoil and scattered particle scattering angles, a clear peak corresponding to the p - ^8He elastic scattering was identified. Spurious asymmetries such as imbalances in the detector efficiency and solid angle were canceled out by reversing the direction of target polarization. It should be emphasized again that the operation of the polarized target in a low magnetic field allowed us to detect recoil protons with an angular resolution sufficient to identify the elastic scattering events.

The measured differential cross sections ($d\sigma/d\Omega$) and analyzing powers (A_y) for p - ^8He (present) and p - ^6He [19, 20] are shown in Fig. 1 as filled circles and squares, respectively. Published $d\sigma/d\Omega$ data [22] are also plotted as the open symbols. It is known from extensive measurements at 65 MeV [9] that the analyzing powers for p - A scattering from stable nuclei usually take large positive values of ~ 0.9 at the second peak, except for the p - ^4He case in which A_y is almost zero [23]. The present A_y data for p - ^8He and p - ^6He lie between these two cases.

To determine the spin-orbit potentials between a proton and ^8He nucleus, we perform a phenomenological optical model analysis. For the optical model potential, we use a Woods-Saxon form factor with a Thomas-type spin-

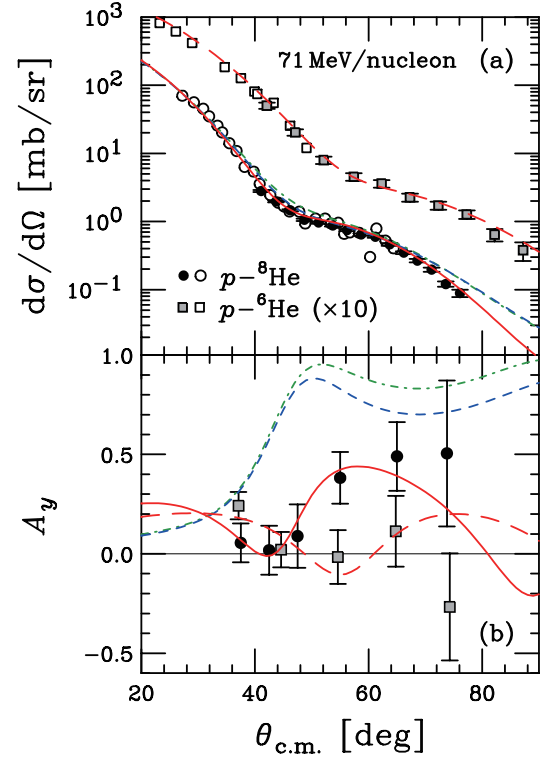


FIG. 1: (Color online) The differential cross section (upper) and analyzing power (lower) of p - $^{6,8}\text{He}$ elastic scattering at 71 MeV/nucleon.

orbit term:

$$U_{\text{OM}}(R) = -V_0 f_r(R) - iW_0 f_i(R) + V_s \frac{2}{R} \frac{d}{dR} f_s(R) \mathbf{L} \cdot \boldsymbol{\sigma}_p + V_C(R) \quad (1)$$

with

$$f_x(R) = \left[1 + \exp\left(\frac{R - r_{0x} A^{1/3}}{a_x}\right) \right]^{-1} \quad (2)$$

$(x = r, i, \text{ or } s).$

Here, \mathbf{R} is the relative coordinate between a proton and a ^8He particle, $\mathbf{L} = \mathbf{R} \times (-i\hbar \nabla_R)$ is the associated angular momentum, and $\boldsymbol{\sigma}_p$ is the Pauli spin operator of the proton. The subscripts r , i , and s denote the real and imaginary parts of the central term and the real part of the spin-orbit term, respectively. V_0 , W_0 and V_s are depth parameters of the corresponding terms. r_{0x} and a_x are radius and diffuseness parameters, respectively. V_C is a Coulomb potential of uniformly charged sphere with a radius of $r_{0C} A^{1/3}$ fm ($r_{0C} = 1.3$ fm). No surface absorption term is considered here. Since the statistics is limited, the imaginary part of the spin-orbit potential is not included in the fits. If we assume it is as small as in the case of stable nuclei, the effect on A_y is within the error bars. However, as it is still unknown whether this assumption holds in unstable nuclei, the imaginary

spin-orbit potential should be investigated in future when sufficient data is available.

Using the optical potential given in Eqs. (1) and (2), we search for a parameter set that reproduces both the $d\sigma/d\Omega$ and A_y data obtained in the present work and the $d\sigma/d\Omega$ data of Ref. [22]. The fit is carried out using the ECIS79 code [24]. The initial values are taken from a set of parameters for p - ^6Li elastic scattering at 72 MeV/nucleon [25]. The solid and long-dashed curves in Fig. 1 show the best-fit results for p - ^8He and p - ^6He , respectively. The reduced chi-square values for $d\sigma/d\Omega$ and A_y are minimized as $\chi^2_{\sigma}/\nu_{\sigma} = 1.91$ and $\chi^2_{A_y}/\nu_{A_y} = 0.37$, respectively, in the p - ^8He case. The optical potential parameters of p - ^6Li [25] and p - ^6He [20] and those obtained for p - ^8He (Set-A) are summarized in Table I. These three potentials are similar to each other, probably because of the resemblance of density distribution. Since ^6Li is also a weakly-bound nucleus, its matter radius and $d\sigma/d\Omega$ are almost identical with those for ^6He as described in Ref. [20]. However, we should note that it is not straightforward to deal with the spin-orbit potential for the ^6Li case, because it has a non-zero spin. Henceforth, the quantitative discussion focuses on the nuclei with spin zero.

The upper panel of Fig. 2 presents the radial dependence of the central terms of the p - ^8He potential (Set-A). The solid, dashed, and dot-dashed curves denote the present potential, that obtained by Koning and Delaroche (KD03) [11], and that obtained by Varner *et al.* (CH89) [10], respectively. A surface absorption term is included in the imaginary term in the case of the global potentials. While the ^8He nucleus is located outside the applicable range of these two global potentials, they serve as guides for comparison since their mass-number dependence is not strong, especially for the spin-orbit term. The real and imaginary terms of the present potential are in reasonable agreement with the global potentials. The root-mean-square (r.m.s.) radii and volume integral of each term are summarized in Table II. The real and imaginary terms of the present potential are comparable to those of the global potentials.

The lower panel of Fig. 2 displays the radial dependence of $RV_{ls}(R)$, which is defined as

$$RV_{ls}(R) = 2V_s \frac{d}{dR} \left[1 + \exp \left(\frac{R - r_{0s} A^{1/3}}{a_s} \right) \right]^{-1}. \quad (3)$$

Here, the R factor on the left-hand side is introduced to cancel the $1/R$ term of the Thomas function in order to present the shape of potential without divergence at small radii. The solid line in Fig. 2 (lower) shows the best-fit potential (Set-A) with a statistical error band (shaded area) corresponding to a potential with $\Delta\chi^2_{A_y} \equiv \chi^2_{A_y} - \chi^2_{A_y:\text{min.}} = 1$. To check the fitting ambiguity of the spin-orbit potential, we search for other possible parameter sets. Excluding very unusual potentials such as ones with $V_0 > 60$ MeV, ten different sets are obtained. In Table I, two of them are presented: Set-B and Set-C

are the results with the deepest and the shallowest spin-orbit potentials, respectively. They are approximately consistent with that of Set-A within the statistical error band as shown in the lower panel of Fig. 2. The obtained spin-orbit potentials have broad peaks at $R \sim 2.2$ fm, whereas the global potentials (dashed and dot-dashed) have sharper peaks at smaller radii of $R \sim 1.6$ fm. The spin-orbit potential for ^8He is found to be shallower and more diffuse than the global systematics of stable nuclei.

To examine the effect of spin-orbit potential on the observables, we compare the results of calculations using different spin-orbit potentials but with identical central potentials. The short-dashed and dot-dashed lines in Fig. 1 correspond to the results of calculations using the same central terms as the present potential but with the spin-orbit terms of the KD03 and CH89 potentials, respectively. These “standard” spin-orbit potentials give large positive A_y values that are incompatible with the current data. It should be stressed that the shallow and diffuse spin-orbit potential is essential in reproducing the present A_y data.

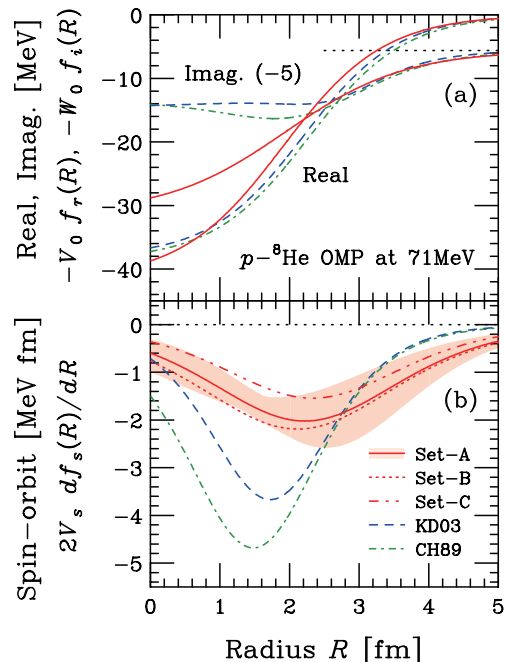


FIG. 2: (Color online) Radial dependence of the optical potential between a proton and a ^8He nucleus.

In Fig. 3, the parameters r_{0s} and a_s are presented for comparison. Filled circles show the parameters determined for spin-zero nuclei ranging from ^4He to ^{28}Si [9, 20, 26]. Parameters for heavier nuclei are represented by the global potentials, KD03 (dashed) and CH89 (dot-dashed), which overlap those of the light nuclei. The present results (Set-A for ^8He) are shown by the filled red circles with uncertainties evaluated in the following manner: For each point in the r_{0s} - a_s plane, a depth parameter V_s is re-searched to minimize the $\chi^2_{A_y}$ value. The solid and dotted lines in the figure indicate regions where

TABLE I: Parameters of the optical potentials for p - ^6Li at 72 MeV/nucleon [25], p - ^6He at 71 MeV/nucleon [20], and p - ^8He at 71 MeV/nucleon (present work).

	V_0 (MeV)	r_{0r} (fm)	a_r (fm)	W_0 (MeV)	r_{0i} (fm)	a_i (fm)	V_s (MeV)	r_{0s} (fm)	a_s (fm)	χ^2_σ/ν_σ	$\chi^2_{A_y}/\nu_{A_y}$
p - ^6Li [25]	31.67	1.10	0.75	14.14	1.15	0.56	3.36	0.90	0.94		
p - ^6He [20]	27.86	1.074	0.681	16.58	0.86	0.735	2.02	1.29	0.76	0.95	0.96
p - ^8He (Set-A)	41.60	0.95	0.73	22.78	0.97	0.86	3.68	1.11	0.91	1.91	0.37
p - ^8He (Set-B)	47.26	0.89	0.75	26.34	0.90	0.88	4.15	1.06	0.95	2.40	0.34
p - ^8He (Set-C)	57.90	0.75	0.80	34.34	0.96	0.74	2.65	1.17	0.86	1.93	0.25

TABLE II: Volume integral and r.m.s. radius of each term of the p - $^{6,8}\text{He}$ potentials at 71 MeV/nucleon.

		J_r/A	J_i/A	$J_{ls}/A^{1/3}$	$\langle r_r^2 \rangle^{1/2}$	$\langle r_i^2 \rangle^{1/2}$	$\langle r_{ls}^2 \rangle^{1/2}$
		(MeV fm ³)			(fm)		(fm)
^6He	Ref. [20]	320	144	66^{+24}_{-26}	2.95	2.98	$3.33^{+0.23}_{-0.26}$
	KD03	419	198	93	2.94	3.07	2.37
	CH89	466	232	108	3.01	3.25	2.29
^8He	Set-A	371	261	107^{+35}_{-41}	3.08	3.52	$3.58^{+0.25}_{-0.20}$
	KD03	413	191	95	3.04	3.22	2.52
	CH89	455	235	114	3.11	3.40	2.44

$\Delta\chi_{A_y}^2 = 1$ and 3, respectively. The radius and diffuseness parameters of the spin-orbit potentials obtained for the neutron-rich helium isotopes appear to be larger than those for the stable nuclei. In contrast, the depth parameters for ^6He and ^8He , determined as $2.02^{+0.82}_{-0.86}$ MeV and $3.68^{+0.80}_{-0.91}$ MeV, respectively, are smaller than the typical value of ~ 5 MeV.

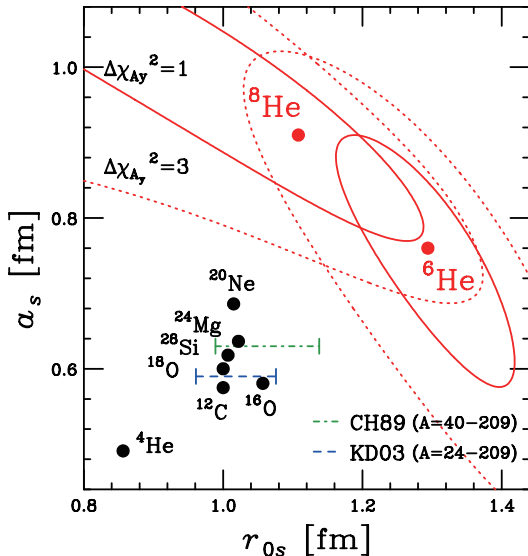


FIG. 3: (Color online) Two-dimensional distribution of the radius and diffuseness parameters of the spin-orbit term of the local (filled circles) and global (dot-dashed: CH89, dashed: KD03) potentials for spin-zero nuclei. Solid and dotted lines indicate $\Delta\chi_{A_y}^2 = 1$ and 3, respectively.

The shape and magnitude of the spin-orbit potential can be discussed in terms of the r.m.s. radius $\langle r_{ls}^2 \rangle^{1/2}$ and the amplitude of $RV_{ls}(R)$ at the peak position. These quantities provide more robust features of the spin-orbit potentials than the individual parameters that couple with each other. Figure 4(a) shows the mass-number dependence of the $\langle r_{ls}^2 \rangle^{1/2}$ values of the potentials for the spin-zero nuclei. The symbols are the same as those in Fig. 3. We can see that the $\langle r_{ls}^2 \rangle^{1/2}$ values of the present potentials (in red; $3.33^{+0.23}_{-0.26}$ fm for ^6He and $3.58^{+0.25}_{-0.20}$ fm for ^8He) are significantly larger than the systematics of the stable nuclei. Moreover, it is interesting to note that a close similarity is found between the mass-number dependence of $\langle r_{ls}^2 \rangle^{1/2}$ and that of the matter radius r_m [27–30], plotted as the open squares in Fig. 4(a). The enhancement seen in the r_m values of ^6He and ^8He is more distinct in the behavior of the $\langle r_{ls}^2 \rangle^{1/2}$ values, which indicates the particular sensitivity of the spin-orbit interaction to the nuclear surface structure.

Figure 4(b) displays the amplitude of $RV_{ls}(R)$ at the peak position $R = r_{0s}A^{1/3}$, which is denoted by $V_s/2a_s$. The peak amplitudes of the local potentials for a stable nuclei are in the range 3.5–5.5 MeV fm and are almost independent of the mass number. Those of the global potentials (dashed and dot-dashed lines) are consistent with these amplitudes. However, the peak depths of the present potentials, $1.32^{+0.25}_{-0.21}$ MeV fm for ^6He and $2.03^{+0.58}_{-0.54}$ MeV fm for ^8He , are smaller than the standard values. From these results, we can conclude that the spin-orbit potentials between a proton and neutron-rich ^6He and ^8He nuclei are both shallower and more diffuse than the global systematics of nuclei along the stability line. This is considered to be a consequence of the diffuse density distribution of these neutron-rich isotopes.

In summary, vector analyzing powers have been measured for the proton elastic scattering from ^8He at 71 MeV/nucleon to investigate the spin-orbit potential between a proton and a neutron-rich ^8He nucleus. The measured differential cross sections and analyzing powers were analyzed using a phenomenological optical model to derive the overall characteristics of the p - $^{6,8}\text{He}$ interactions. The spin-orbit potentials for ^6He and ^8He were found to be both shallower and more diffuse than the global systematics of stable nuclei. The r.m.s. radius of these spin-orbit potentials deviate from the well-

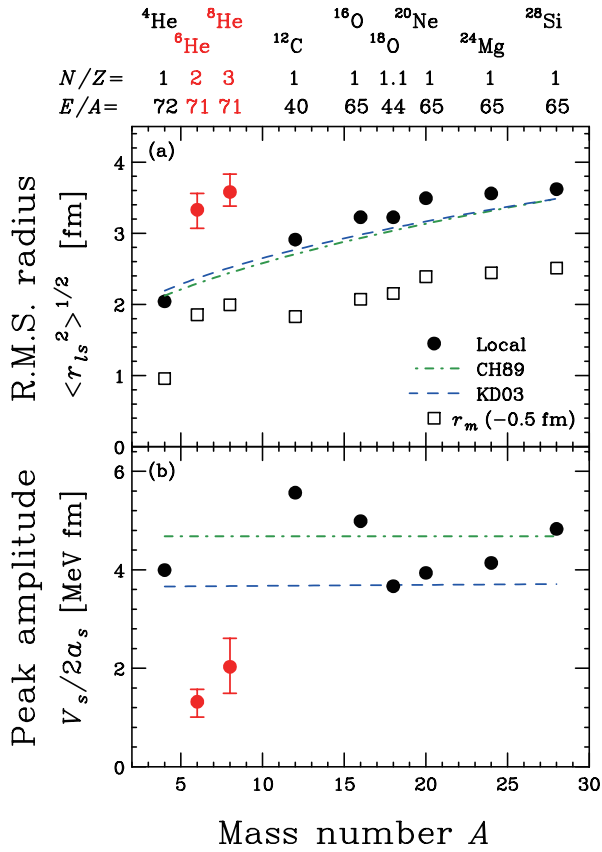


FIG. 4: (Color online) The $\langle r_{ls}^2 \rangle^{1/2}$ and r_m (upper) values and the peak amplitude $V_s/2a_s$ (lower) of the spin-orbit potentials for light spin-zero nuclei. For ${}^8\text{He}$, the results of Set-A are shown. Those with Sets-B and -C are consistent with them within the statistical uncertainties. The symbols for r_m are shifted horizontally by -0.5 fm to prevent overlap.

established mass-number dependence and show a close similarity to the behavior of the matter radius. Depths of the obtained potentials were found to be significantly reduced from the standard value. The shallow and diffuse spin-orbit potentials for ${}^6\text{He}$ and ${}^8\text{He}$ are considered to be a consequence of the diffuse density distribution of these two neutron-rich helium isotopes.

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